BRL-TR-3188

DTIC FILE COPY

2

TECHNICAL REPORT BRL-TR-3188

BRL

AD-A231 020

HEATS OF EXPLOSION AT LOW PRESSURES
II.

ARTHUR COHEN
MARTIN S. MILLER
HUGHES E. HOLMES
BONITA A. HUNTLEY

DECEMBER 1990

U.S. ARMY LABORATORY COMMAND

BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

NOTICES

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	December 1990	Final Oct 89 - Jan 90

4. TITLE AND SUBTITLE
HEATS OF EXPLOSION AT LOW PRESSURES. II.

5. FUNDING NUMBERS
1L161102AH43

6. AUTHOR(S)
Arthur Cohen, Martin S. Miller
Hughes E. Holmes, Bonita A. Huntley

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-5066

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
BRL-TR-3188

11. SUPPLEMENTARY NOTES
Part I of this report is BRL-TR-3024, dated August 1989. The title and the authors are the same.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

An alternate method for estimating the thermal energy (E) of propellant combustion products in guns at low pressures has been investigated. The method assumes that for same pressure levels in guns and calorimeter bombs, E is equal to the measured heat of explosion (HEX). HEX have been measured in calorimeters for M30 and XM39 at low initial pressures (Po) (25-1015 psia). Low loading densities (LD) (.0002-.012 g/cc) were used to minimize the uncertainty in the calorimeter pressure level during combustion. The values for HEX, at the higher LD, imply that combustion is complete. As Po and LD decrease, a fall off in HEX from the values obtained at the higher LD is observed. This is attributed to a change in the combustion mechanism which leads to incomplete combustion. HEX values in the fall off region are also dependent on the physical environment in the calorimeter. This implies that some knowledge of the physical processes which occur during combustion at low pressures in calorimeter bombs (and guns) is required to assess the usefulness of estimating values for E from the HEX measurements.

14. SUBJECT TERMS	15. NUMBER OF PAGES
Heats of Explosion, Propellants, M30, LOVA, Heat of Combustion, Low Pressure	25
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std. Z39-18
298-102

INTENTIONALLY LEFT BLANK

TABLE OF CONTENTS

INTENTIONALLY LEFT BLANK

LIST OF FIGURES

INTENTIONALLY LEFT BLANK

ACKNOWLEDGEMENTS

The authors would like to thank E. Freedman (Eli Freedman & Associates, Baltimore, MD) for help with the BLAKE calculations and T. Tingle (Parr Instrument Co., Moline, IL) for helpful suggestions concerning operation of the calorimeters.

INTENTIONALLY LEFT BLANK

I. INTRODUCTION

The work presented in this report is a continuation of a former program[1] in which the pressure dependence of heats of explosion (HEX) for RDX (secondary explosive), XM39 (RDX composite propellant) and M30 (triple base propellant) were determined. The measurements were made in calorimeter bombs which were prepressurized to various levels with inert gas (He or N_2). Low loading densities (.0002-.012 g/cc) were used in order to minimize the transient pressure increase during combustion.

The program was started to provide information which could help improve interior ballistic (IB) code predictions of gun performance at low pressures. The discrepancies between measurements and predictions of ignition delays and pressurization rate in guns and gun simulators was discussed at a recent JANNAF workshop.[2] It is generally believed that the discrepancies at low pressures are due to two assumptions: (1) infinite-rate kinetics (to calculate the rate of energy production) and (2) thermodynamic chemical equilibrium (to calculate the thermal energy (E) of the propellant combustion products). The validity of these assumptions becomes questionable as pressure decreases. The absence of thermochemical equilibrium among combustion products under low pressure conditions is not unexpected. It is consistent with the HEX measurements at low pressures[1] and with strand burner observations of two stage propellant flames[1,3] where, below a critical pressure, the second stage (and thermochemical equilibrium) is inhibited. The use of finite rate kinetics will, in principle, eliminate the need for both these assumptions but acquiring the necessary information for incorporation into the codes will take time. The objective of the program was to evaluate an alternate method for estimating values of E which is independent of the thermochemical equilibrium assumption and can be incorporated into the IB codes relatively quickly. This alternate method is to substitute for the value of E at a given gun pressure the HEX value measured at the same pressure in calorimeter bombs. This implicitly assumes that combustion and cooling processes in bombs and guns are similar. If this assumption is valid then the HEX measurements at various pressurization levels are expected to be better estimates of E than the calculated themochemical equilibrium values that are now being used in IB codes. There is the additional requirement (for use in the IB codes) that these processes depend primarily on total pressure (i.e., are not strongly dependent on gas composition).

The earlier work[1] showed that as initial (inert) pressures (Po) and loading densities (LD) decreased there was a fall off in measured HEX and ignition became more difficult. The goal of this work is to extend the HEX measurements to lower LD in order to minimize uncertainties in the pressurization level in the calorimeter. At low LD the ignition energy can be comparable to the combustion energy and must be subtracted from the (total) thermal energy of the calorimeter to obtain HEX values.

II. EXPERIMENTAL TECHNIQUE

The experimental technique has been described previously.[1] HEX were measured with a Parr Calorimeter System. The bombs (volume = 340 cc) were modified to provide for transient pressure measurements and sampling of combustion products. The data

reported here are for perforated propellant grains except for a few XM39 data which were taken with propellant slabs (solid).

It was possible to obtain data for M30 at lower LD (and Po) by using larger diameter (.016" vs .006" Ni) ignition wire and increasing the wire area in contact with the propellant, i.e., increasing ignition power and energy to the propellant. These data are denoted in Table 1 as enhanced ignition. For XM39, it was also necessary to place Zirconia Felt (Zicar Products), a thermal insulator, at the bottom of the capsule which supports the grains in the calorimeter during ignition and flamespreading (i.e., decrease the the heat transferred from the propellant) in order to obtain data (denoted in Table 2 as thermal insulation) at lower LD.

TABLE 1. M30

Po (psia)	Gas	m (g)	<HEX> (cal/g)	Nh	Sh (cal/g)	<p*> (psi)	Np	Sp (psi)
1015	He	1	963	2	9	476	2	196
1015	N_2	1	977	2	9	329	2	49
1015	He	.28	943	5	7	131	5	55
1015	N_2	.28	945	2	10	108	2	5
1015	He	.16	893	2	46	103	2	5
1015	He	.08	838	4	32	60	2	1
465	He	1	958	2	20	628	2	52
465	He	.28	956	3	19	89	3	43
165	He	1	943	4	8	352	2	81
165	N_2	1	913	2	4	301	1	--
165	He	.28	923	3	6	57	3	28
165	N_2	.28	870	1	--	93	1	--
65	He	1	927	3	11	200	2	56
65	He	.28	864	2	32	---	0	--
65	N_2	.28	777	2	12	61	2	1
45	He	1	918	5	17	171	4	39
45	He	.28	818	4	11	34	4	13
25	He	1	911	3	34	190	1	--
25	N_2	1	928	2	13	---	0	--
25*	He	.28	693	6	81	17	5	9
25*	N_2	.28	723	2	29	25	2	18
25*	He	.16	826	2	119	12	2	1
25*	He	.08	587	2	176	13	2	1

* = Enhanced ignition.

TABLE 2. XM39								
Po (psia)	Gas	m (g)	<HEX> (cal/g)	Nh	Sh (cal/g)	<P*> (psi)	Np	Sp (psi)
1045+	He	4.4	829	1	--	---	0	--
940	He	2.2	830	2	0	(600)	1	--
940	N_2	2.2	835	1	--	1072	1	--
940	He	.52	810	3	12	272	1	--
940	N_2	.52	802	2	5	216	1	--
940	He	.24	794	4	23	123	4	8
940	He	.13	731	2	4	80	2	10
940	He	.07	661	2	90	38	2	12
795+	He	2.2	822	1	--	---	0	--
545+	He	4.4	833	1	--	---	0	--
465	He	2.2	825	2	3	(600)	1	--
465	N_2	2.2	823	1	--	880	1	--
465	He	.52	810	2	7	182	2	4
465	N_2	.52	798	2	27	163	2	4
295+	He	4.4	830	1	--	---	0	--
245+	He	4.4	832	1	--	---	0	--
245+	He	2.2	807	1	--	---	0	--
240	He	2.2	825	2	4	452	1	--
240	N_2	2.2	819	2	2	594	2	24
240	He	.52	769	2	36	123	2	4
240	N_2	.52	759	2	11	128	2	7
165	He	2.2	812	2	14	312	2	78
165	N_2	2.2	804	1	--	480	1	--
165	He	.52	739	5	51	71	5	15
165	N_2	.52	712	2	14	86	2	7
45	He	2.2	818	2	25	108	1	--
45	He	.52	711	2	29	29	2	1
45$*	He	.24	578	3	82	7	2	1
45$*	He	.14	581	3	57	7	2	1
45$*	He	.07	529	2	83	7	2	4

+ = Slab
$ = Thermal insulation
* = Enhanced ignition

The ignition energy was obtained by integrating (over time) the product of the instantaneous ignition voltage and current. The Parr Calorimeter System uses a transformer to provide a 60 Hz ignition voltage. This was measured. The ignition current was measured using a Pearson current monitor (Model #411) (Pearson Electronics, Inc.).

III. EXPERIMENTAL RESULTS

Figure 1 shows the instantaneous ignition voltage, ignition current and calculated ignition energy using .016" Ni ignition wire for an experiment with 1.03 g M30 propellant in N_2, Po = 465 psia. The ignition energy is 18.3 cal. which is about 2% of the total heat measured in the calorimeter. Figure 2 shows the corresponding pressure increment which is obtained from the piezoelectric transducer signal. The pressure measurement is subject to error due to heating of the piezoelectric transducer during the experiment. Efforts were made to minimize this heating by shielding with vacuum grease but were not entirely successful. At present, it has been assumed that the maximum pressure increments (P*) are not greatly affected by changes in heating due to differences in LD.

The data reported earlier[1] did not include corrections for ignition energy. These corrections have been made for the data presented in Tables 1 and 2. Table 1 summarizes the HEX and P* measurements for M30. m is the sample mass (±10%), < > signifies the mean of the measurements, Nh and Np are the number of HEX and P* measurements, respectively, Sh and Sp are the corresponding standard deviations. The corresponding information for XM39 is given in Table 2.

Various plots of the data in Tables 1 and 2 are shown in Figures 3 through 8. Figure 3 is a plot of HEX vs. Po for M30 which shows the effects of changes in mass and ambient gas on the measurements. At Po ≥ 465 psia, for both m = 1 g and m = .28 g, HEX values are relatively constant (~950 cal/g) and (at Po = 1015) equal in He and N_2. At Po ≤ 165 psia, for m = 1 g in He, there is some indication of a fall off in HEX values. At Po ≤ = 165 psia and m = .28 g, the fall off is obvious for both gases and HEX appear to be smaller in N_2 than in He (data at Po = 25 psia have large scatter).

Figure 4 is the corresponding plot for XM39. HEX appear to be equal for grains (perforated) and slabs (solid) and slightly less in N_2 than in He. At Po ≥ 465 psia, the HEX values for m ≥ 2.2 g are relatively constant (~820 cal/g) and those for m = .52 g are slightly smaller but also appear to be constant (~800 cal/g). At Po ≤ 240 psia there is little change in HEX with m ≥ 2.2 g but there is an obvious fall off in HEX for m = .52 g (in both He and N_2).

Figure 5 is a plot of HEX vs. m for M30. This figure shows the fall off in HEX with m (or LD) at two different initial pressures. The fall off for Po = 1015 psia is noticeable at m < .28 g. At m = .08 g, HEX = 838 cal/g and the corresponding operating pressure range (Po → (Po+P*) for values of Po and P* listed in Table 1) is 1015-1075 psia. For Po = 25 psia the fall off in HEX with m is noticeable at m = 1 g. The fall off appears to be interrupted between m = .08 g and m = .28 g, data taken under "enhanced ignition" conditions. These data have large scatter and the change in behavior may not be real.

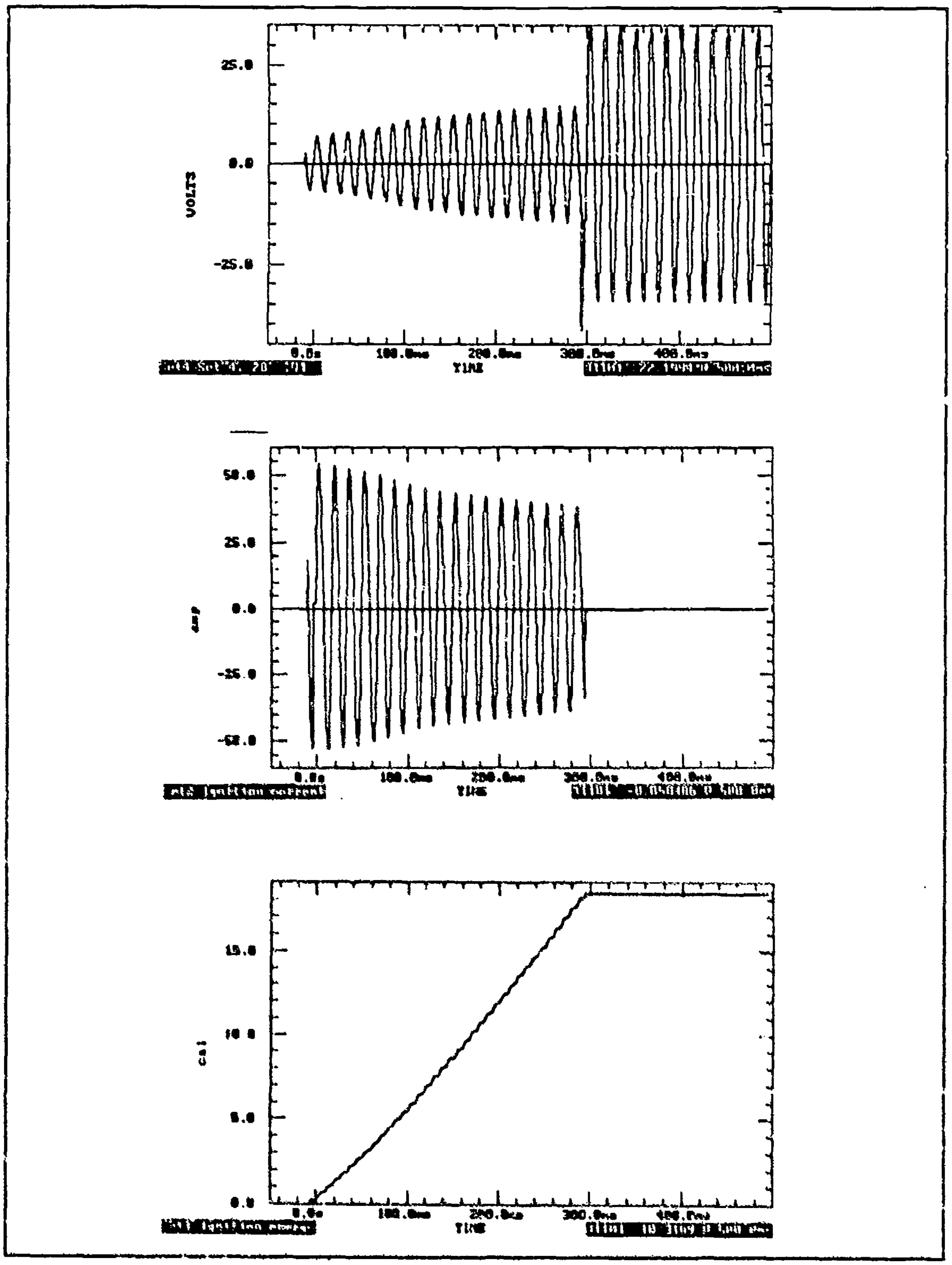

Figure 1. Ignition Characteristics of Parr Calorimeter System with .016" Ni Fuse Wire . (a) Ignition voltage (60 Hz): increase in voltage at Time = 294 ms is due to cessation of current flow. (b) Ignition current (60 Hz). (c) Ignition energy: calculated from integration (overtime) of the product of instantaneous voltage and current shown in (a) and (b).

At m = .08 g, HEX = 587 cal/g and the corresponding operating pressure range is 25-38 psia.

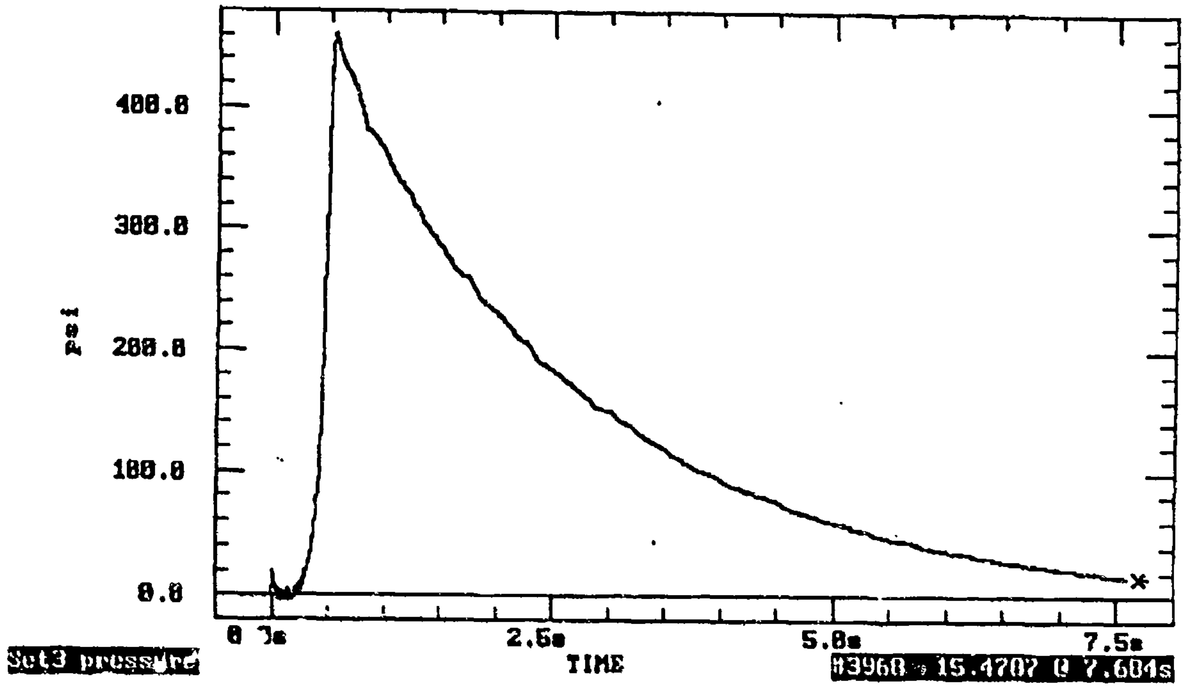

Figure 2. Piezoelectric Transducer Signal: Transient Pressure During Combustion and Cooling in the Calorimeter. Signal was processed by a 30 Hz electronic filter to reduce noise during ignition.

Figure 6 is the corresponding plot (to Fig. 3) for XM39 data. The fall off in HEX with m for Po = 940 psia is noticeable at m < .52 g. At m = .07 g, HEX = 661 cal/g and the corresponding operating pressure range is 940-978 psia. For Po = 45 psia, the fall off starts at m < 2.2 g. At m = .07 g, HEX=629 cal/g and the corresponding operating pressure range is 45-52 psia.

The fall off in HEX with m at fixed Po and especially for small values of m suggest that HEX are not solely dependent on the operating pressure level in the calorimeter. This will make it difficult to use measured HEX for estimating values for E.

The data in Figure 7 demonstrates that HEX for M30 is not solely dependent on pressure levels in the bomb during burning, but can depend on loading density. The data for .26 and 1.0 g (light points) indicate that HEX increase slightly with maximum total pressure (initial pressure + measured maximum pressure increment) but are not greatly dependent on mass. The data for .08 and .16 g (dark points) have initial pressures (i.e., minimum bomb pressures) = 1000 psia. HEX for these data are lower than HEX for the data obtained at higher loading densities (seven points) although five of the latter data have maximum bomb pressures < 600 psia. For these experiments, it appears that HEX depend more strongly on loading density (i.e., the concentration of combustion products in the bomb) than on pressure levels.

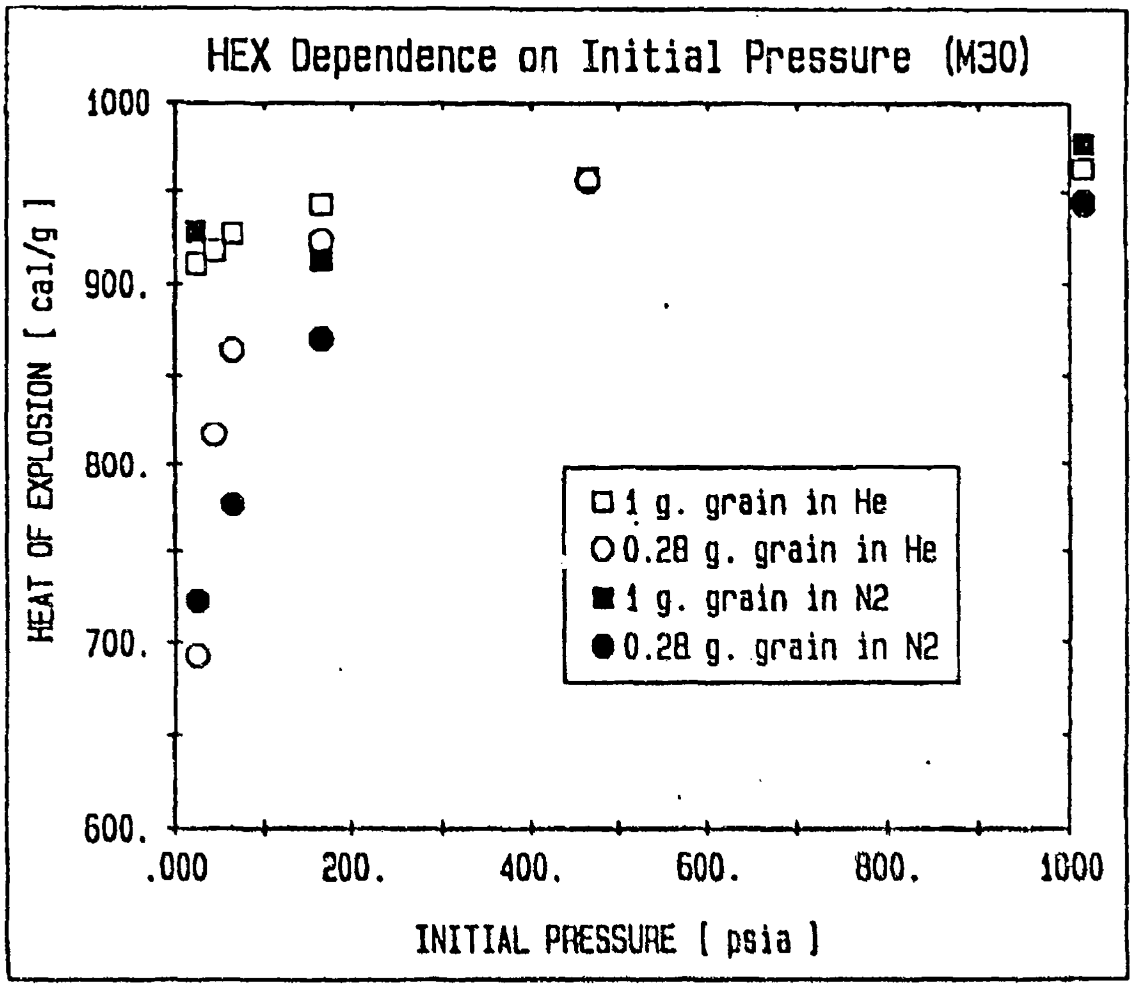

Figure 3. Dependence of Experimental Heats of Explosiion on Initial Pressure for M30

Figure 8 is the corresponding plot (to Figure 7) for XM39 data. All data with total maximum pressures > 800 psia have Po = 940 psia. The other data have maximum total pressure < 800 psia. Despite lower operating pressures in the calorimeter, HEX values for m = 2.2 g with maximum total pressures < 700 psia appear to be greater than those those for m = .07, .13, and .24 g. This stronger dependence on loading density than on pressure is similar to the M30 behavior shown in Figure 7.

IV. DISCUSSION OF RESULTS

The data in Figure 3 for 1 g M30 suggests that HEX are not greatly dependent on Po for Po ≥ 25 psia and on pressurizing gas composition. The differences between measured HEX (911-977 cal/g) and those calculated (~955 cal/g) assuming a (generally accepted) freeze-out temperature greater than 1500 K is not great. This suggests that for Po > 25 psia combustion in the calorimeter is almost complete (i.e., combustion products correspond to a thermochemical equilibrium mixture) for 1 g samples. Comparison of

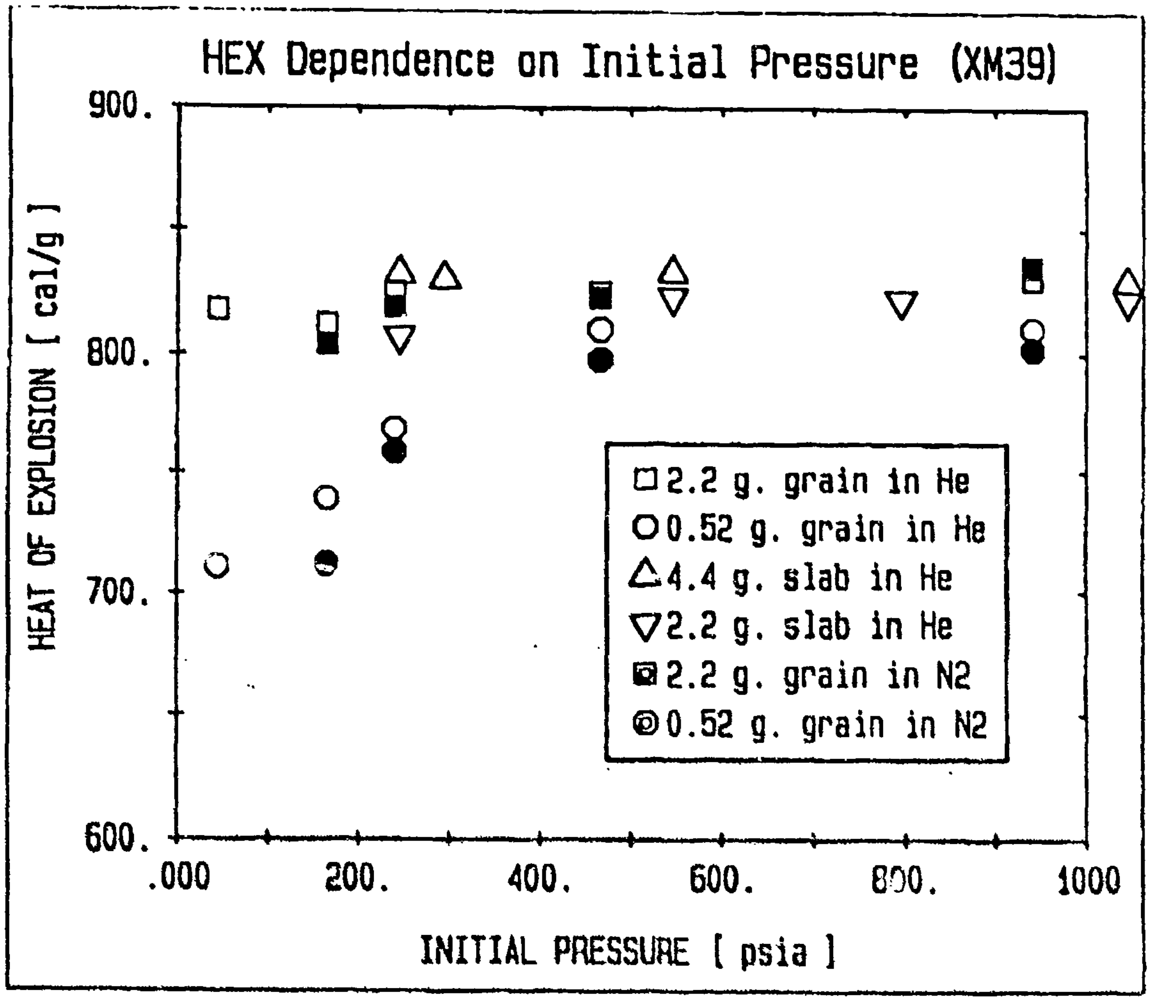

Figure 4. Dependence of Experimental Heats of Explosion on Initial Pressure for XM39

measured and calculated HEX values for .28 g M30, at Po = 465 and 1015 psia also indicate that combustion is almost complete. At lower Po (<465 psia) there is a fall off in HEX from the calculated values (the calculated values are not greatly dependent on Po or LD) for the .28 g samples. This fall off suggests that changes occur in the combustion mechanism (or extent of reaction) at low pressures which inhibit the establishment of thermochemical equilibrium among combustion products.

The data in Figure 4 for 2.2 g and 4.4 g XM39 indicate that differences between measured HEX (800-835 cal/g) and calculated values (~810 cal/g) are small suggesting that combustion is complete. Comparisons of the HEX values (798-810 cal/g) for .52 g XM39 with calculated values indicate that combustion is complete at Po > 465 psia. At lower Po there is fall off in HEX values from calculated values, similar to the behavior with M30, indicative of changes in the combustion mechanism at low pressures and deviations of combustion products from thermochemical equilibrium.

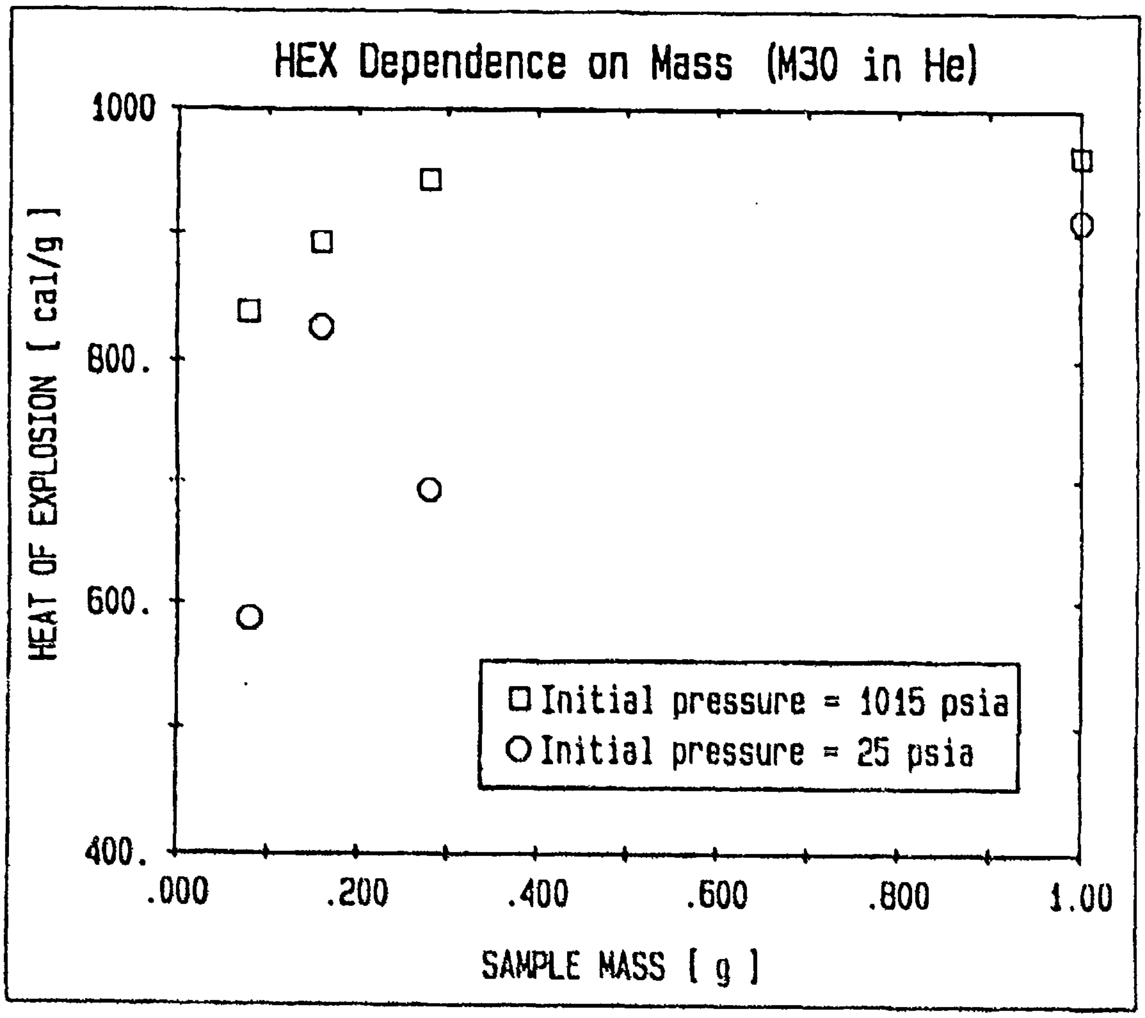

Figure 8. Dependence of Experimental Heats of Explosion on Loading Density for M30

The HEX calculations and reasons for the HEX dependence on initial pressures and loading densities has been discussed previously.[1] The transition at lower Po and LD from complete to incomplete combustion is attributed to a decrease in chemical kinetic rates and the subsequent increased importance of transport rates (diffusion and heat transfer) in the combustion process. This increased dependence on transport processes under these conditions is thought to be responsible for the increase in variability of the data at low Po and low LD which can be seen from the values of the standard deviations (s) in Tables 1 and 2. The small decrease in HEX when N_2 is substituted for He at low Po and low LD may be due to differences in transport properties of the gases.

The thermochemical properties of the propellant combustion products presently used in IB codes are those calculated for closed bomb combustion products in thermochemical equilibrium at loading densities between .2 - .33 g/cc. Blake[4] calculations for M30 under these conditions give values for E (which do not greatly depend on LD) near 1025 cal/g. If the alternate method for estimating E which is now under consideration (i.e., for a given pressure measured HEX and E values are equal) is valid then the HEX

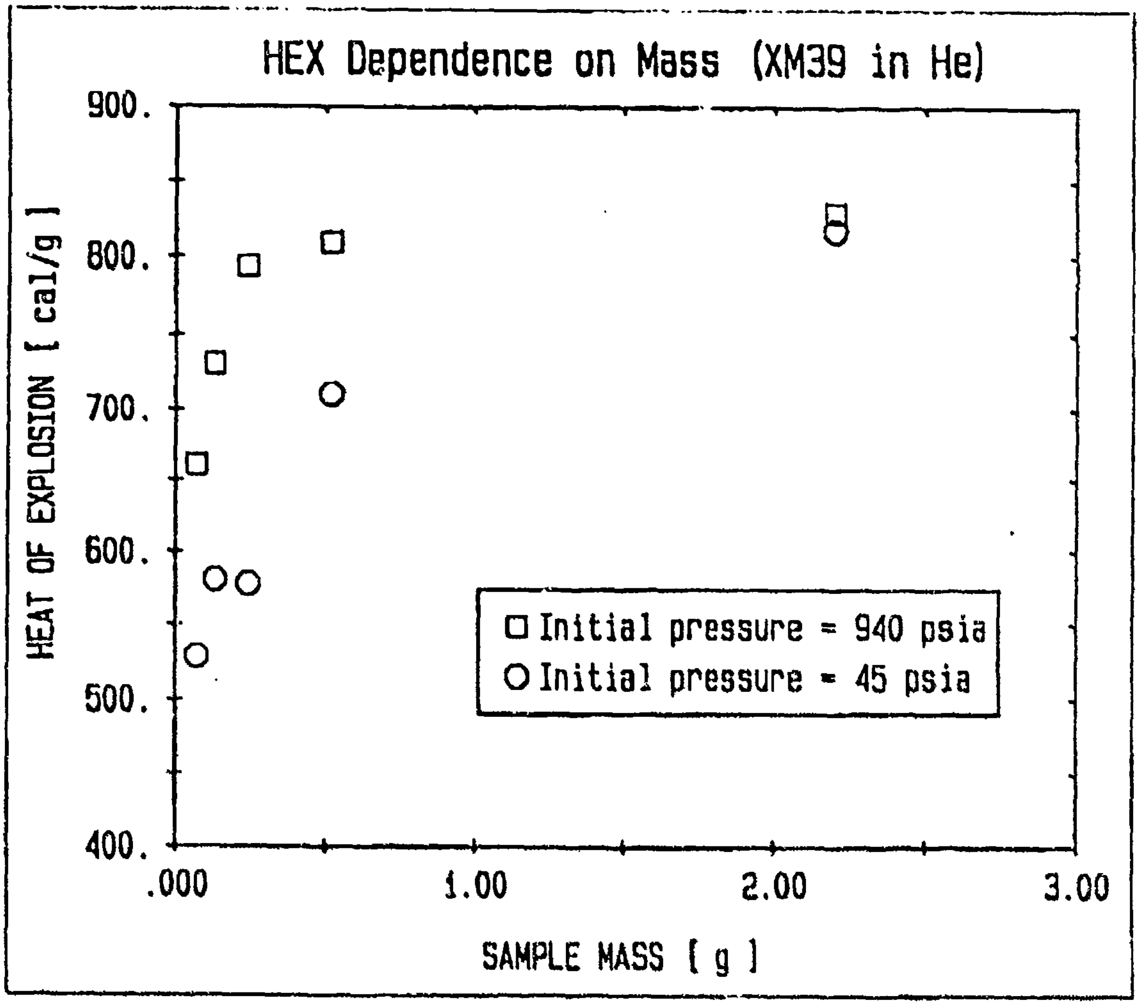

Figure 6. Dependence of Experimental Heats of Explosion on Loading Density for XM39

values for M30 in Figure 5 at m = .08 g indicate that in the pressure range 1015-1075 psia, E ~838 cal/mole and in the pressure range 25-38 psia, E ~587 cal/g. Although the corresponding standard deviations for these measurements are quite large, 32 and 176 cal/g, the difference between the calculated E and measured HEX are statistically significant for both the high and low pressure ranges.

For XM39, the calculated E ~895 cal/g. The HEX values for XM39 in Figure 6 at m = .07 g indicate that in the pressure range 940-978 psia, E ~731 cal/g and in the range 45-52 psia, E ~529 cal/g. The corresponding standard deviations (4 and 83 cal/g) indicate that the differences between calculated E and those based on the HEX measurements are significant.

Lower values for E may improve IB code predictions at low pressures but the substitution of measured HEX values for E in IB calculations requires that they be independent of LD (i.e., dependent only on total pressure in the calorimeter). It is necessary to determine if values for HEX measured at the lowest LD (m = .08 and .07 g

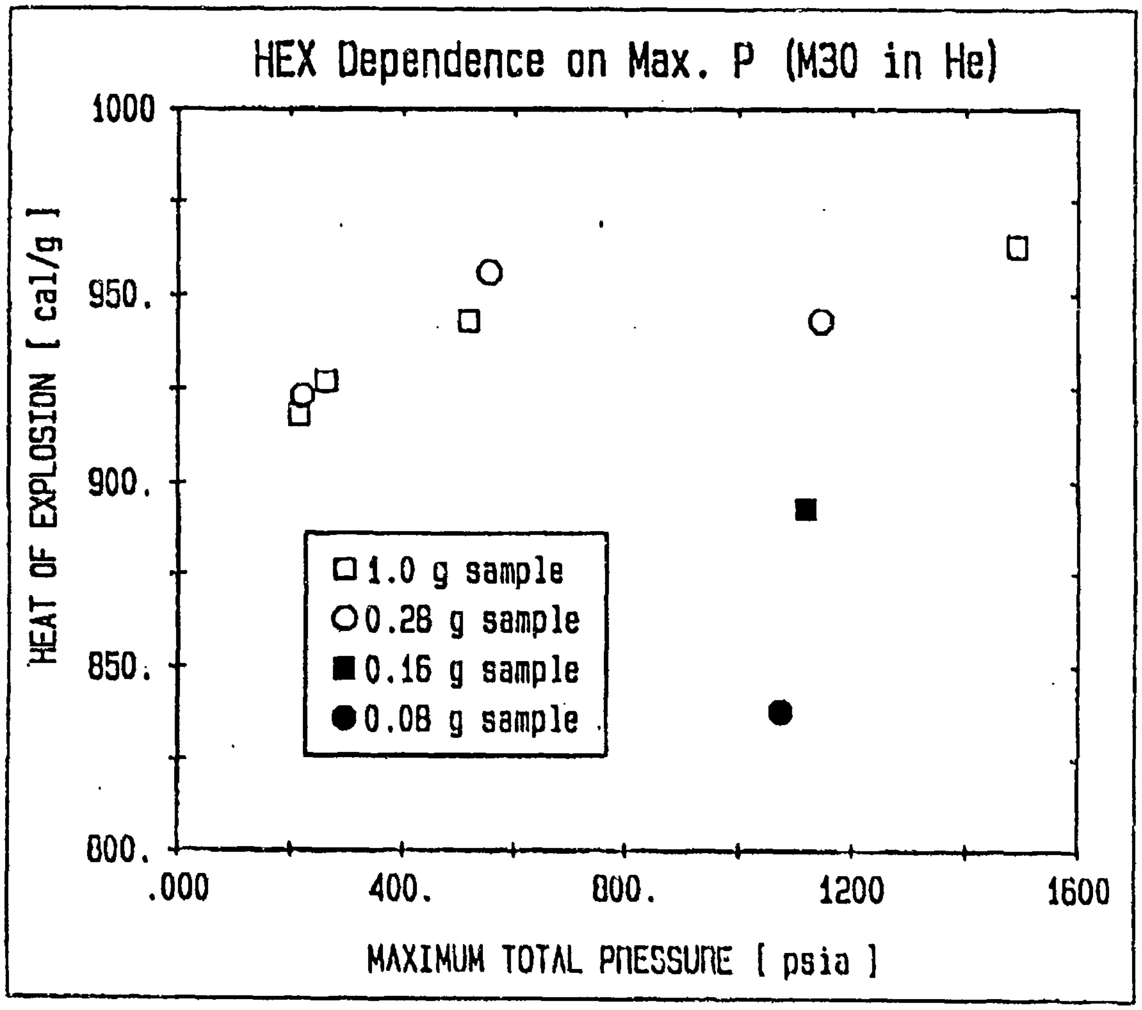

Figure 7. Maximum Total Pressure and Heats of Explosion: Selected M30 Data to Show Pressure and Loading Density Effects on Experimental Heats of Explosion

in Figures 5 and 6, respectively) which have been used to make esimates of E, are consistent with this requirement. The data in Figures 7 and 8 indicate that HEX values are affected by changes in LD which suggests that the HEX have some dependence on the concentration of combustion products in addition to the operating pressure levels in the calorimeter.

It is noteworthy to emphasize that the effect of systematic errors in the calorimeter determination of thermal energy can greatly affect HEX values. Determination of the calorimeter energy equivalent which is used to convert the calorimeter temperature increase into energy is obtained by a standardization method in which increases in the calorimeter temperature are approximately 3° C. At low loading densities (m = .07 g), the increases in temperature are approximately .03° C. Conclusions based on the low loading density HEX values remain questionable without determining the validity of using the calorimeter energy equilivalent for such small increases in temperature.

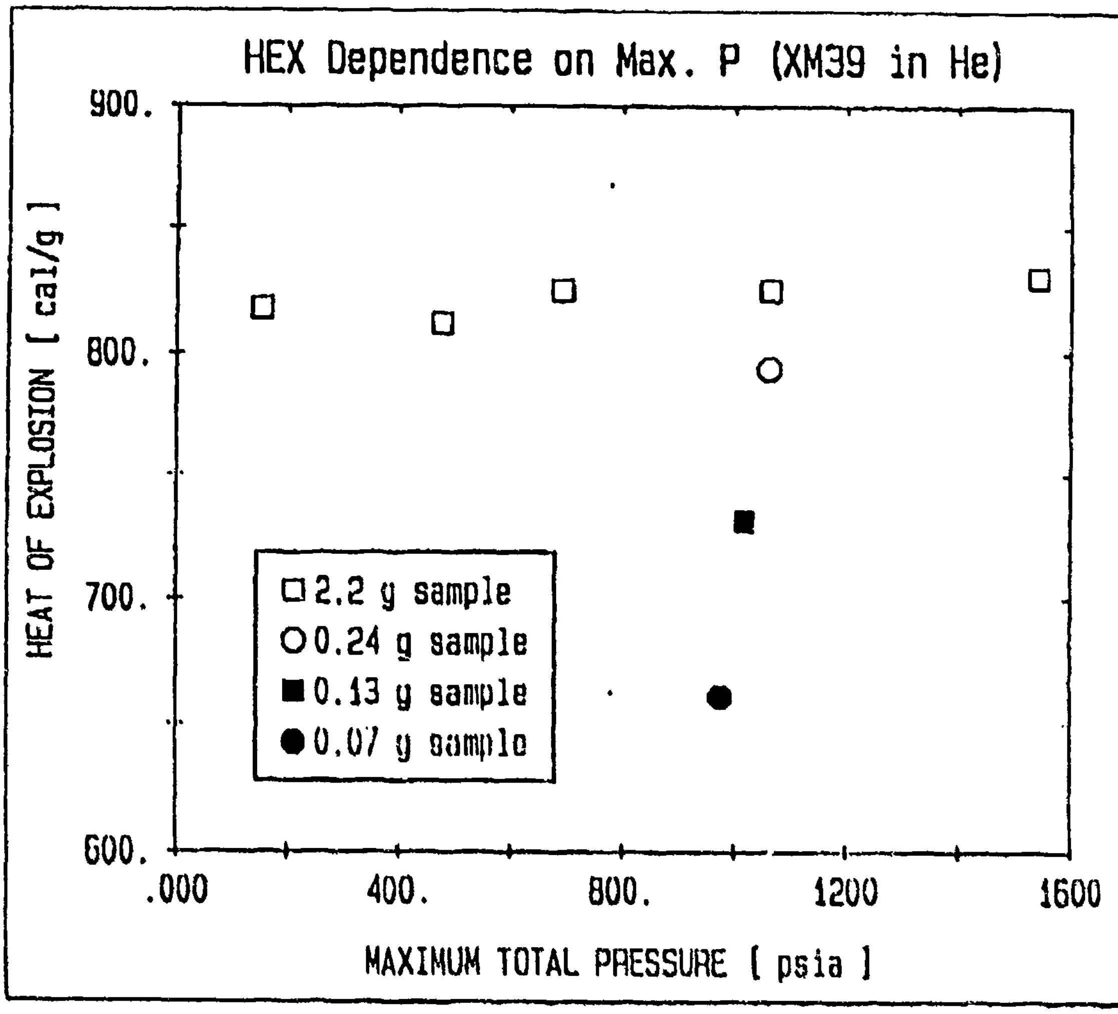

Figure 8. Maximum Total Pressure and Heats of Explosion: Selected XM39 Data to Show Pressure and Loading Effects on Experimental Heats of Explosion

V. SUMMARY

An alternate method for estimating the thermal energy (E) of propellant combustion products for calculating gun performance at low pressures has been investigated. The method assumes that at a given gun pressure, E is equal to the measured heat of explosion (HEX). HEX have been measured in calorimeters for M30 and XM39 at low initial pressures (Po) (26-1016 psia). Low loading densities (LD) (.012 - .0002 g/cc) were used to minimize the uncertainty in the calorimeter pressure during combustion. At the higher LD, HEX values for M30 and XM39 were constant and not much different from HEX values calculated for an equilibrium combustion process. As Po and LD decrease, a fall off in HEX from the values obtained at higher LD and higher Po is observed. The HEX values in this low pressure fall off region are much less than calculated HEX and also the calculated E values now used in gun calculations. HEX values in the fall off region may

also depend on the concentration of combustion products in the calorimeter. This latter dependence will increase the difficulties of using the HEX measurements in IB codes.

The HEX measurements in the fall off region are also dependent on the physical environment. The addition of thermal insulation to the capsule which support the propellant grains and changes in its location relative to the grains which affect transport processes during combustion also affect HEX values.[1] This implies that some knowledge of the physical processes which occur during combustion at low pressures in calorimeter bombs (and guns) will be required to asses the usefullness of estimating values for E from the HEX measurements.

Future work to determine the magnitude of the calorimeter errors in measuring small thermal inputs is planned and an effort will be made to obtain information on the sensitivity of HEX measurements to the presence of combustion product gases and to simulated (inert) propellant grains.

REFERENCES

1. A. Cohen, M.S. Miller, H.E. Holmes, and B.A. Huntley, "Heats of Explosion at Low Pressures", BRL Technical Report BRL-TR-3024, August 1989.

2. G.E. Keller, "Report on JANNAF Workshop: Influence of Gas Phase Chemical Kinetics on Low Pressure Ignition and Flamespreading in Solid Propellants", BRL-TR-2918, July 1988.

3. N. Kubota and T. Masamoto, "Flame Structure and Burning Rate Characteristics of CMDB Propellants", 16th Symposium (International) on Combustion, p. 1201, The Combustion Institute, 1976.

4. E. Freedman, "BLAKE - A Thermodynamics Code Based on Tiger: Users Guide Manual", BRL Technical Report ARBRL-TR-02411, July 1982.

No of Copies	Organization
2	Administrator Defense Technical Info Center ATTN: DTIC-DDA Cameron Station Alexandria, VA 22304-6145
1	HQDA (SARD-TR) WASH DC 20310-0001
1	Commander US Army Materiel Command ATTN: AMCDRA-ST 5001 Eisenhower Avenue Alexandria, VA 22333-0001
1	Commander US Army Laboratory Command ATTN: AMSLC-DL Adelphi, MD 20783-1145
2	Commander US Army, ARDEC ATTN: SMCAR-IMI-I Picatinny Arsenal, NJ 07806-5000
2	Commander US Army, ARDEC ATTN: SMCAR-TDC Picatinny Arsenal, NJ 07806-5000
1	Director Benet Weapons Laboratory US Army, ARDEC ATTN: SMCAR-CCB-TL Watervliet, NY 12189-4050
1	Commander US Army Armament, Munitions and Chemical Command ATTN: SMCAR-ESP-L Rock Island, IL 61299-5000
1	Director US Army Aviation Research and Technology Activity ATTN: SAVRT-R (Library) M/S 219-3 Ames Research Center Moffett Field, CA 94035-1000

No of Copies	Organization
1	Commander US Army Missile Command ATTN: AMSMI-RD-CS-R (DOC) Redstone Arsenal, AL 35898-5010
1	Commander US Army Tank-Automotive Command ATTN: AMSTA-TSL (Technical Library) Warren, MI 48397-5000
1	Director US Army TRADOC Analysis Command ATTN: ATRC-WSR White Sands Missile Range, NM 88002-5502
(Class. only)1	Commandant US Army Infantry School ATTN: ATSH-CD (Security Mgr.) Fort Benning, GA 31905-5660
(Unclass. only)1	Commandant US Army Infantry School ATTN: ATSH-CD-CSO-OR Fort Benning, GA 31905-5660
1	Air Force Armament Laboratory ATTN: AFATL/DLODL Eglin AFB, FL 32542-5000

Aberdeen Proving Ground

No of Copies	Organization
2	Dir, USAMSAA ATTN: AMXSY-D AMXSY-MP, H. Cohen
1	Cdr, USATECOM ATTN: AMSTE-TD
3	Cdr, CRDEC, AMCCOM ATTN: SMCCR-RSP-A SMCCR-MU SMCCR-MSI
1	Dir, VLAMO ATTN: AMSLC-VL-D

No. of Copies	Organization
4	Commander US Army Research Office ATTN: R. Ghirardelli D. Mann R. Singleton R. Shaw P.O. Box 12211 Research Triangle Park, NC 27709-2211
2	Commander US Army, ARDEC ATTN: SMCAR-AEE-B, D.S. Downs SMCAR-AEE, J.A. Lannon Picatinny Arsenal, NJ 07806-5000
1	Commander US Army, ARDEC ATTN: SMCAR-AEE-BR, L. Harris Picatinny Arsenal, NJ 07806-5000
2	Commander US Army Missile Command ATTN: AMSMI-RK, D.J. Ifshin W. Wharton Redstone Arsenal, AL 35898
1	Commander US Army Missile Command ATTN: AMSMI-RKA, A.R. Maykut Redstone Arsenal, AL 35898-5249
1	Office of Naval Research Department of the Navy ATTN: R.S. Miller, Code 432 800 N. Quincy Street Arlington, VA 22217
1	Commander Naval Air Systems Command ATTN: J. Ramnarace, AIR-54111C Washington, DC 20360
1	Commander Naval Surface Warfare Center ATTN: J.L. East, Jr., G-23 Dahlgren, VA 22448-5000
2	Commander Naval Surface Warfare Center ATTN: R. Bernecker, R-13 G.B. Wilmot, R-16 Silver Spring, MD 20903-5000

No. of Copies	Organization
5	Commander Naval Research Laboratory ATTN: M.C. Lin J. McDonald E. Oran J. Shnur R.J. Doyle, Code 6110 Washington, DC 20375
1	Commanding Officer Naval Underwater Systems Center Weapons Dept. ATTN: R.S. Lazar/Code 36301 Newport, RI 02840
2	Commander Naval Weapons Center ATTN: T. Boggs, Code 388 T. Parr, Code 3895 China Lake, CA 93555-6001
1	Superintendent Naval Postgraduate School Dept. of Aeronautics ATTN: D.W. Netzer Monterey, CA 93940
3	AL/LSCF ATTN: R. Corley R. Geisler J. Levine Edwards AFB, CA 93523-5000
1	AL/MKPB ATTN: B. Goshgarian Edwards AFB, CA 93523-5000
1	AFOSR ATTN: J.M. Tishkoff Bolling Air Force Base Washington, DC 20332
1	OSD/SDIO/IST ATTN: L. Caveny Pentagon Washington, DC 20301-7100
1	Commandant USAFAS ATTN: ATSF-TSM-CN Fort Sill, OK 73503-5600
1	F.J. Seiler ATTN: S.A. Shackleford USAF Academy, CO 80840-6528

No. of Copies	Organization
1	University of Dayton Research Institute ATTN: D. Campbell AL/PAP Edwards AFB, CA 23523
1	NASA Langley Research Center Langley Station ATTN: G.B. Northam/MS 168 Hampton, VA 23365
4	National Bureau of Standards ATTN: J. Hastie M. Jacox T. Kashiwagi H. Se-erjian US Department of Commerce Washington DC 20234
1	Aerojet Solid Propulsion Co. ATTN: P. Micheli Sacramento, GA 95813
1	Applied Combustion Technology, Inc. ATTN: A.M. Varney P.O. Box 607885 Orlando, FL 32860
2	Applied Mechanics Reviews The American Society of Mechanical Engineers ATTN: R.E. White A.B. Wenzel 345 E. 47th Street New York, NY 10017
1	Atlantic Research Corp. ATTN: M.K. King 5390 Cherokee Avenue Alexandria, VA 22314
1	Atlantic Research Corp. ATTN: R.H.W. Waesche 7511 Wellington Road Gainesville, VA 22065
1	AVCO Everett Research Laboratory Division ATTN: D. Stickler 2385 Revere Beach Parkway Everett, MA 02149

No. of Copies	Organization
1	Battelle Memorial Institute Tactical Technology Center ATTN: J. Huggins 505 King Avenue Columbus, OH 43201
1	Cohen Professional Services ATTN: N.S. Cohen 141 Channing Street Redlands, CA 92373
1	Exxon Research & Eng. Co. ATTN: A. Dean Route 22E Annandale, NJ 08801
1	Ford Aerospace and Communications Corp. DIVAD Division Div. Hq., Irvine ATTN: D. Williams Main Street & Ford Road Newport Beach, CA 92663
1	General Applied Science Laboratories, Inc. 77 Raynor Avenue Ronkonkama, NY 11779-6649
1	General Electric Ordnance Systems ATTN: J. Mandzy 100 Plastics Avenue Pittsfield, MA 01203
2	General Motors Rsch Labs Physics Department ATTN: T. Sloan R. Teets Warren, MI 48090
2	Hercules, Inc. Allegheny Ballistics Lab. ATTN: W.B. Walkup E.A. Yount P.O. Box 210 Rocket Center, WV 26726
1	Honeywell, Inc. Government and Aerospace Products ATTN: D.E. Broden/ MS MN50-2000 600 2nd Street NE Hopkins, MN 55343

No. of Copies	Organization
1	Honeywell, Inc. ATTN: R.E. Tompkins MN38-3300 10400 Yellow Circle Drive Minnetonka, MN 55343
1	IBM Corporation ATTN: A.C. Tam Research Division 5600 Cottle Road San Jose, CA 95193
1	IIT Research Institute ATTN: R.F. Remaly 10 West 35th Street Chicago, IL 60616
2	Director Lawrence Livermore National Laboratory ATTN: C. Westbrook M. Costantino P.O. Box 808 Livermore, CA 94550
1	Lockheed Missiles & Space Co. ATTN: George Lo 3251 Hanover Street Dept. 52-35/B204/2 Palo Alto, CA 94304
1	Los Alamos National Lab ATTN: B. Nichols T7, MS-B284 P.O. Box 1663 Los Alamos, NM 87545
1	National Science Foundation ATTN: A.B. Harvey Washington, DC 20550
1	Olin Ordnance ATTN: V. McDonald, Library P.O. Box 222 St. Marks, FL 32355-0222
1	Paul Gough Associates, Inc. ATTN: P.S. Gough 1048 South Street Portsmouth, NH 03801-5423

No. of Copies	Organization
2	Princeton Combustion Research Laboratories, Inc. ATTN: M. Summerfield N.A. Messina 475 US Highway One Monmouth Junction, NJ 08852
1	Hughes Aircraft Company ATTN: T.E. Ward 8433 Fallbrook Avenue Canoga Park, CA 91303
1	Rockwell International Corp. Rocketdyne Division ATTN: J.E. Flanagan/HB02 6633 Canoga Avenue Canoga Park, CA 91304
4	Sandia National Laboratories Division 8354 ATTN: R. Cattolica S. Johnston P. Mattern D. Stephenson Livermore, CA 94550
1	Science Applications, Inc. ATTN: R.B. Edelman 23146 Cumorah Crest Woodland Hills, CA 91364
3	SRI International ATTN: G. Smith D. Crosley D. Golden 333 Ravenswood Avenue Menlo Park, CA 94025
1	Stevens Institute of Tech. Davidson Laboratory ATTN: R. McAlevy, III Hoboken, NJ 07030
1	Sverdrup Technology, Inc. LERC Group ATTN: R.J. Locke, MS SVR-2 2001 Aerospace Parkway Brook Park, OH 44142
1	Thiokol Corporation Elkton Division ATTN: S.F. Palopoli P.O. Box 241 Elkton, MD 21921

No. of Copies	Organization
1	Morton Thiokol, Inc. Huntsville Division ATTN: J. Deur Huntsville, AL 35807-7501
3	Thiokol Corporation Wasatch Division ATTN: S.J. Bennett P.O. Box 524 Brigham City, UT 84302
1	United Technologies Research Center ATTN: A.C. Eckbreth East Hartford, CT 06108
3	United Technologies Corp. Chemical Systems Division ATTN: R.S. Brown T.D. Myers (2 copies) P.O. Box 49028 San Jose, CA 95161-9028
1	Universal Propulsion Company ATTN: H.J. McSpadden Black Canyon Stage 1 Box 1140 Phoenix, AZ 85029
1	Veritay Technology, Inc. ATTN: E.B. Fisher 4845 Millersport Highway P.O. Box 305 East Amherst, NY 14051-0305
1	Brigham Young University Dept. of Chemical Engineering ATTN: M.W. Beckstead Provo, UT 84058
1	California Institute of Tech. Jet Propulsion Laboratory ATTN: L. Strand/MS 512/102 4800 Oak Grove Drive Pasadena, CA 91009
1	California Institute of Technology ATTN: F.E.C. Culick/ MC 301-46 204 Karman Lab. Pasadena, CA 91125
1	University of California Los Alamos Scientific Lab. P.O. Box 1663, Mail Stop B216 Los Alamos, NM 87545

No. of Copies	Organization
1	University of California, Berkeley Chemistry Deparment ATTN: C. Bradley Moore 211 Lewis Hall Berkeley, CA 94720
1	University of California, San Diego ATTN: F.A. Williams AMES, B010 La Jolla, CA 92093
2	University of California, Santa Barbara Quantum Institute ATTN: K. Schofield M. Steinberg Santa Barbara, CA 93106
1	University of Colorado at Boulder Engineering Center ATTN: J. Daily Campus Box 427 Boulder, CO 80309-0427
2	University of Southern California Dept. of Chemistry ATTN: S. Benson C. Wittig Los Angeles, CA 90007
1	Case Western Reserve Univ. Div. of Aerospace Sciences ATTN: J. Tien Cleveland, OH 44135
1	Cornell University Department of Chemistry ATTN: T.A. Cool Baker Laboratory Ithaca, NY 14853
1	University of Delaware ATTN: T. Brill Chemistry Department Newark, DE 19711
1	University of Florida Dept. of Chemistry ATTN: J. Winefordner Gainesville, FL 32611

No. of Copies	Organization
3	Georgia Institute of Technology School of Aerospace Engineering ATTN: E. Price W.C. Strahle B.T. Zinn Atlanta, GA 30332
1	University of Illinois Dept. of Mech. Eng. ATTN: H. Krier 144MEB, 1206 W. Green St. Urbana, IL 61801
1	Johns Hopkins University/APL Chemical Propulsion Information Agency ATTN: T.W. Christian Johns Hopkins Road Laurel, MD 20707
1	University of Michigan Gas Dynamics Lab Aerospace Engineering Bldg. ATTN: G.M. Faeth Ann Arbor, MI 48109-2140
1	University of Minnesota Dept. of Mechanical Engineering ATTN: E. Fletcher Minneapolis, MN 55455
3	Pennsylvania State University Applied Research Laboratory ATTN: K.K. Kuo H. Palmer M. Micci University Park, PA 16802
1	Pennsylvania State University Dept. of Mechanical Engineering ATTN: V. Yang University Park, PA 16802
1	Polytechnic Institute of NY Graduate Center ATTN: S. Lederman Route 110 Farmingdale, NY 11735

No. of Copies	Organization
2	Princeton University Forrestal Campus Library ATTN: K. Brezinsky I. Glassman P.O. Box 710 Princeton, NJ 08540
1	Purdue University School of Aeronautics and Astronautics ATTN: J.R. Osborn Grissom Hall West Lafayette, IN 47906
1	Purdue University Department of Chemistry ATTN: E. Grant West Lafayette, IN 47906
2	Purdue University School of Mechanical Engineering ATTN: N.M. Laurendeau S.N.B. Murthy TSPC Chaffee Hall West Lafayette, IN 47906
1	Rensselaer Polytechnic Inst. Dept. of Chemical Engineering ATTN: A. Fontijn Troy, NY 12181
1	Stanford University Dept. of Mechanical Engineering ATTN: R. Hanson Stanford, CA 94305
1	University of Texas Dept. of Chemistry ATTN: W. Gardiner Austin, TX 78712
1	University of Utah Dept. of Chemical Engineering ATTN: G. Flandro Salt Lake City, UT 84112
1	Virginia Polytechnic Institute and State University ATTN: J.A. Schetz Blacksburg, VA 24061

No. of Copies	Organization	No. of Copies	Organization
1	Freedman Associates ATTN: E. Freedman 2411 Diana Road Baltimore, MD 21209-1525		

INTENTIONALLY LEFT BLANK.

USER EVALUATION SHEET/CHANGE OF ADDRESS

This Laboratory undertakes a continuing effort to improve the quality of the reports it publishes. Your comments/answers to the items/questions below will aid us in our efforts.

1. BRL Report Number BRL-TR-3188 Date of Report December 1990

2. Date Report Received ______

3. Does this report satisfy a need? (Comment on purpose, related project, or other area of interest for which the report will be used.) ______

4. Specifically, how is the report being used? (Information source, design data, procedure, source of ideas, etc.) ______

5. Has the information in this report led to any quantitative savings as far as man-hours or dollars saved, operating costs avoided, or efficiencies achieved, etc? If so, please elaborate. ______

6. General Comments. What do you think should be changed to improve future reports? (Indicate changes to organization, technical content, format, etc.) ______

CURRENT ADDRESS

Name

Organization

Address

City, State, Zip Code

7. If indicating a Change of Address or Address Correction, please provide the New or Correct Address in Block 6 above and the Old or Incorrect address below.

OLD ADDRESS

Name

Organization

Address

City, State, Zip Code

(Remove this sheet, fold as indicated, staple or tape closed, and mail.)

FOLD HERE

DEPARTMENT OF THE ARMY
Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 210[illegible]-5066

OFFICIAL BUSINESS

NO POSTAGE NECESSARY IF MAILED IN THE UNITED STATES

BUSINESS REPLY MAIL
FIRST CLASS PERMIT No 0001, APG, MD

POSTAGE WILL BE PAID BY ADDRESSEE

Director
U.S. Army Ballistic Research Laboratory
ATTN: SLCBR-DD-T
Aberdeen Proving Ground, MD 21005-9989

FOLD HERE